A Radiation Closure Study of Arctic Cloud Properties using the Fu-Liou RTM

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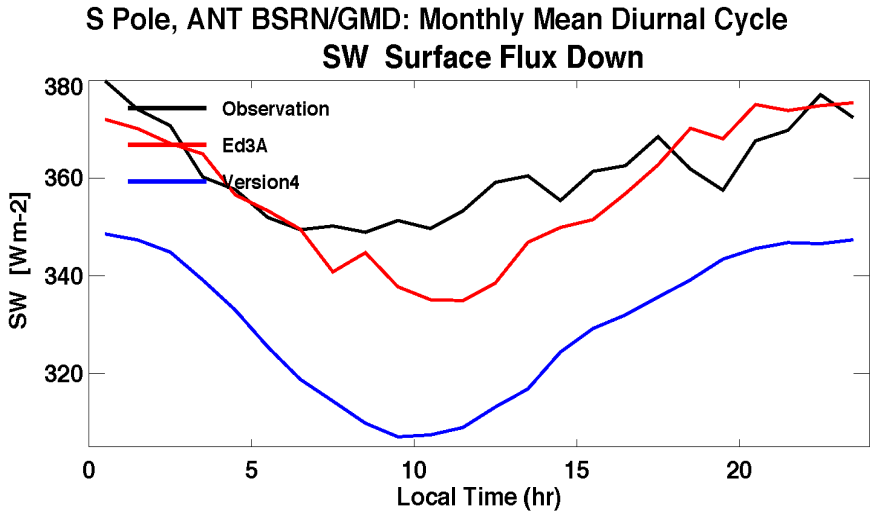
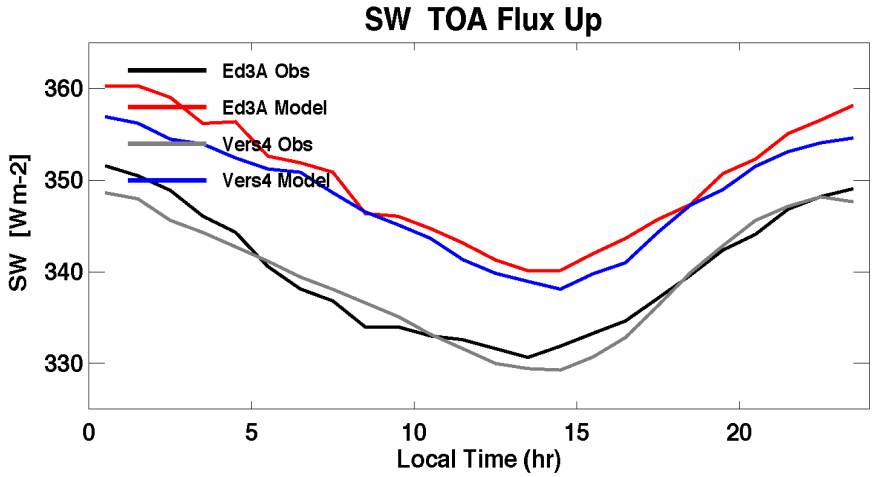
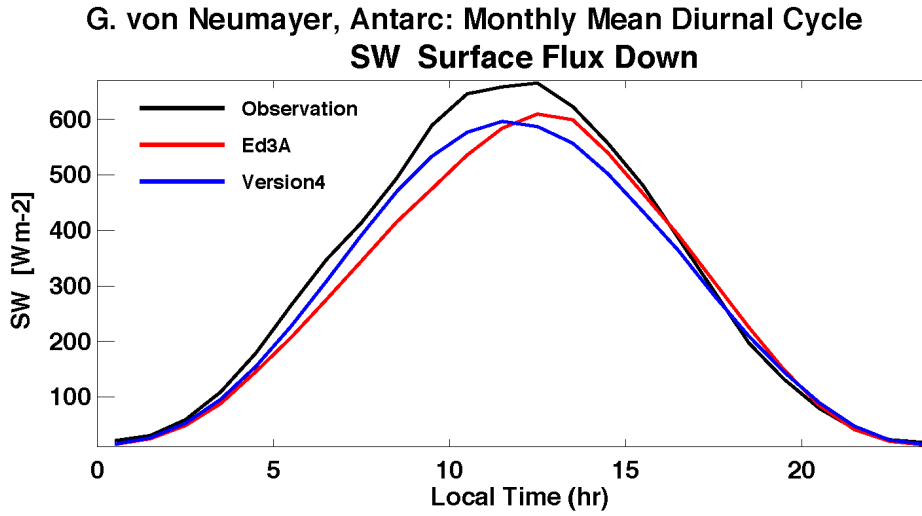
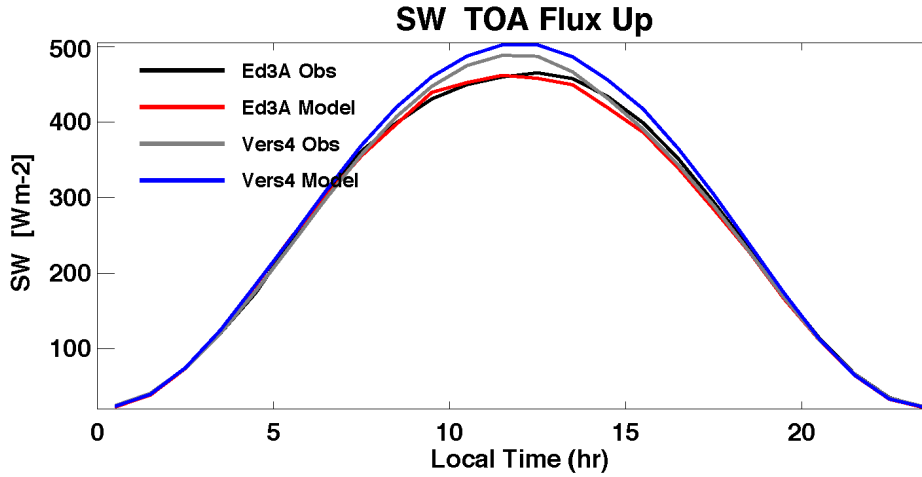








Surface SW down of Ed2 agrees with observations, and Ed4 is lower, indicating Ed4 tau is larger, consistent to its higher TOA SW up. But how does Ed2 TOA SW up is also much higher tha observations.

From surface SW down, indicating both Ed2 and Ed4 tau are higher than observations. Ed4 TOA SW up is higher than data, consistent to its tau, but Ed2 TOA SW up agrees perfectly with observations with larger tau.

Location of ARM Northern Slope of Alaska (NSA Site)

1) **Time period: March 2000 to December 2006**
2) **Only single-layered low clouds with liquid dominant mixed-phase clouds have been selected under snow-free (90 cases, surface albedo<0.3) and snow (68 cases, R_{SFC}>0.3) conditions.**
3) **CERES cloud and radiation results are averaged over a grid box of 100 km x 100 km.**

Methodology/Procedure

- **1. Select the single-layered low-level stratus clouds for snow-free cases (90) and snow cases (68)**
- **2. Calculate ARM re and tau using Dong's parameterization (Dong and Mace 2003)**

$$r_e = 2.49\mathrm{LWP} + 10.25(1 - R_{\mathrm{sfc}}^3)\gamma - 0.25\mu_0 + 20.28\mathrm{LWP}\gamma(1 - R_{\mathrm{sfc}}^3) - 3.14\mathrm{LWP}\mu_0,$$

$$\tau = \frac{3\mathrm{LWP}}{2r_e\rho_w}.$$

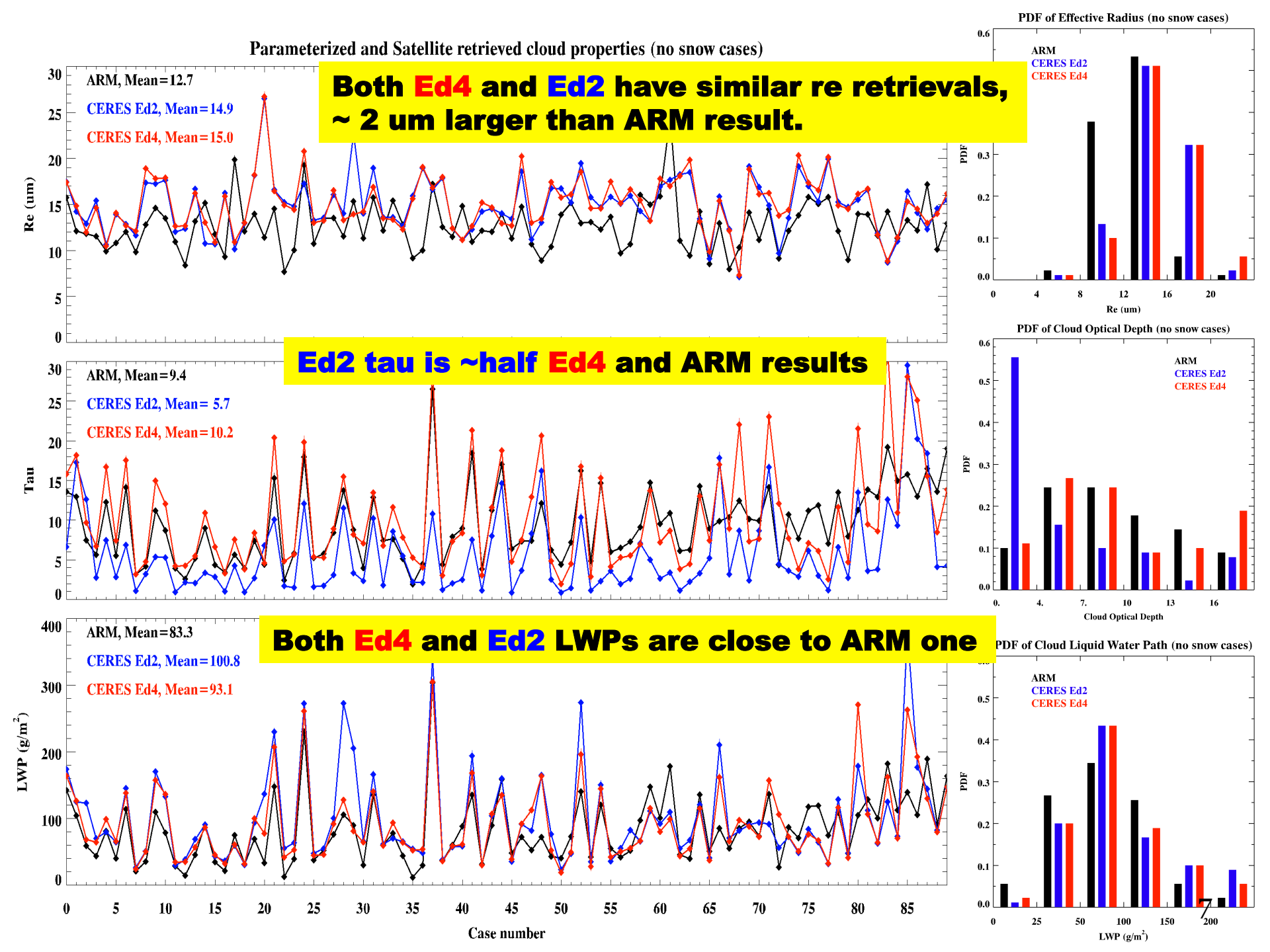
- **3. Calculate the $SW^{\downarrow}$ at surface and $SW^{\uparrow}$ at TOA from Fu-Liou RTM with input of ARM, Ed2 and Ed4 retrieved re and tau, as well as ARM measured cloud-base and –top heights, and surface albedo**
- **4. Compare the calculated surface $SW^{\downarrow}$ fluxes and transmissions (γ=cloudy $SW^{\downarrow}$ to clear-sky $SW^{\downarrow}$) with ARM observed ones, and their TOA $SW^{\uparrow}$ fluxes and albedos with CERES EBAF.**

Questions to answer from this study

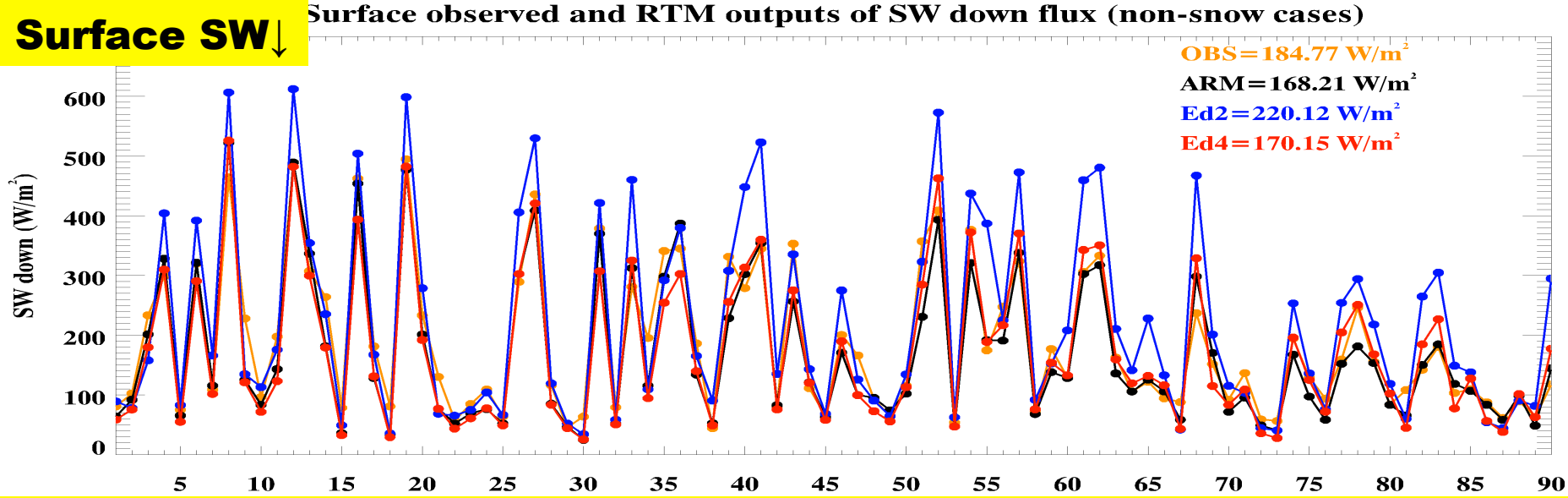
- **1. How do the CERES-MODIS Ed2 and Ed4 cloud microphysical properties compare with ARM's retrievals?**
- **2. How do the model calculated surface and TOA radiation results agree with observations with the input of their cloud properties?**
- **3. How do the surface and TOA radiation results change with cloud optical depth, cosine(solar zenith angle), and surface albedo?**

Snow-Free Cases (90)

THE SURFACE ALBEDO MEASURED BY ARM LESS THAN 0.3

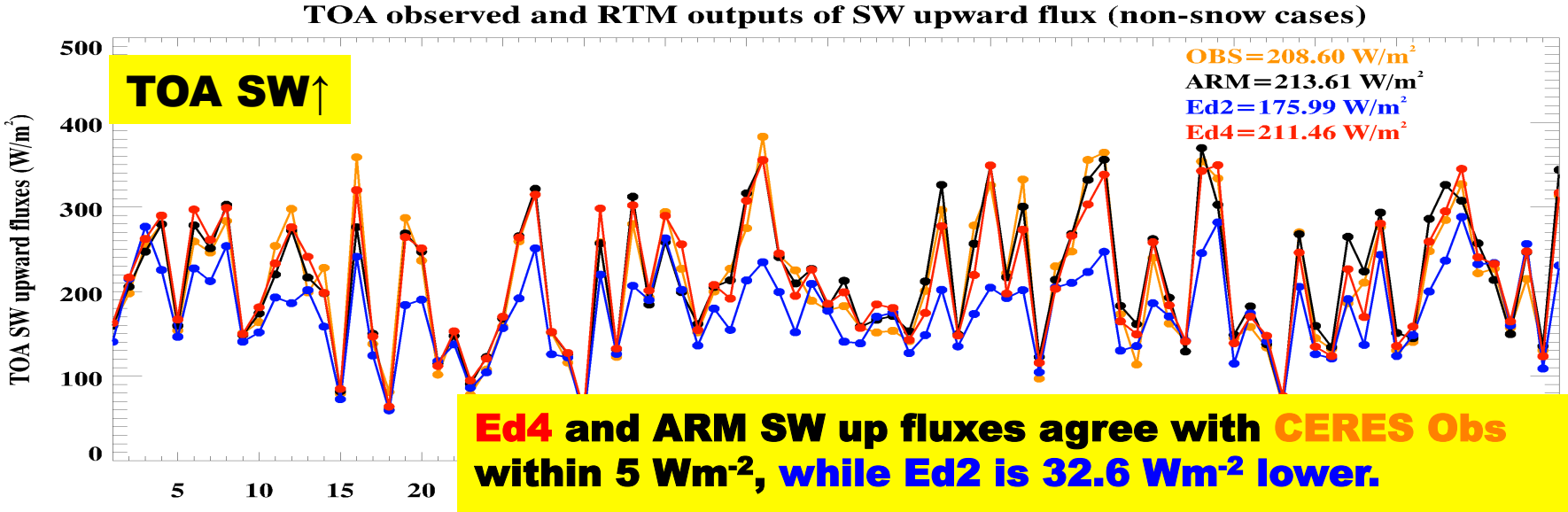

Parameterized and Satellite retrieved cloud properties (no snow cases)
ARM, Mean=12.7
CERES Ed2, Mean=14.9
CERES Ed4, Mean=15.0
Re (um)
Both Ed4 and Ed2 have similar re retrievals, ~ 2 um larger than ARM result.
PDF of Effective Radius (no snow cases)
ARM
CERES Ed2
CERES Ed4
PDF
Re (um)
ARM, Mean=9.4
CERES Ed2, Mean= 5.7
CERES Ed4, Mean=10.2
Tau
Ed2 tau is ~half Ed4 and ARM results
PDF of Cloud Optical Depth (no snow cases)
ARM
CERES Ed2
CERES Ed4
PDF
Cloud Optical Depth
ARM, Mean=83.3
CERES Ed2, Mean=100.8
CERES Ed4, Mean=93.1
LWP (g/m^2)
Both Ed4 and Ed2 LWPs are close to ARM one
PDF of Cloud Liquid Water Path (no snow cases)
ARM
CERES Ed2
CERES Ed4
PDF
LWP (g/m^2)
Case number

Surface SW↓



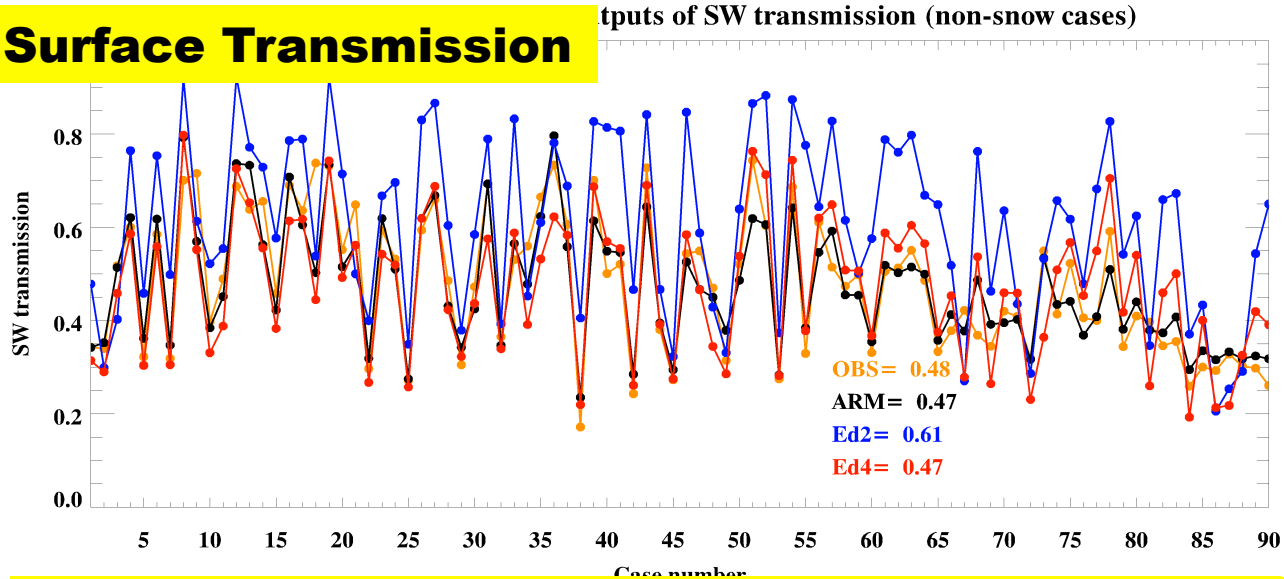
Compared to ARM surface Obs (184.8), Ed4 and ARM are 14.6 Wm^{-2} and 16.6 Wm^{-2} lower, primarily due to clear-sky difference (37.5 Wm^{-2}) between Fu-Liou RTM calculation and observation. Ed2 is 35.3 Wm^{-2} larger, consistent to its lower optical depth (5.7 vs 10.2).

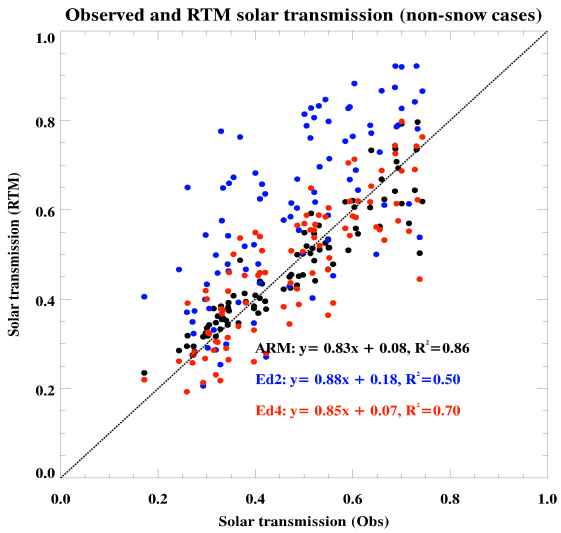
TOA SW↑



Ed4 and ARM SW up fluxes agree with CERES Obs within 5 Wm^{-2}, while Ed2 is 32.6 Wm^{-2} lower.

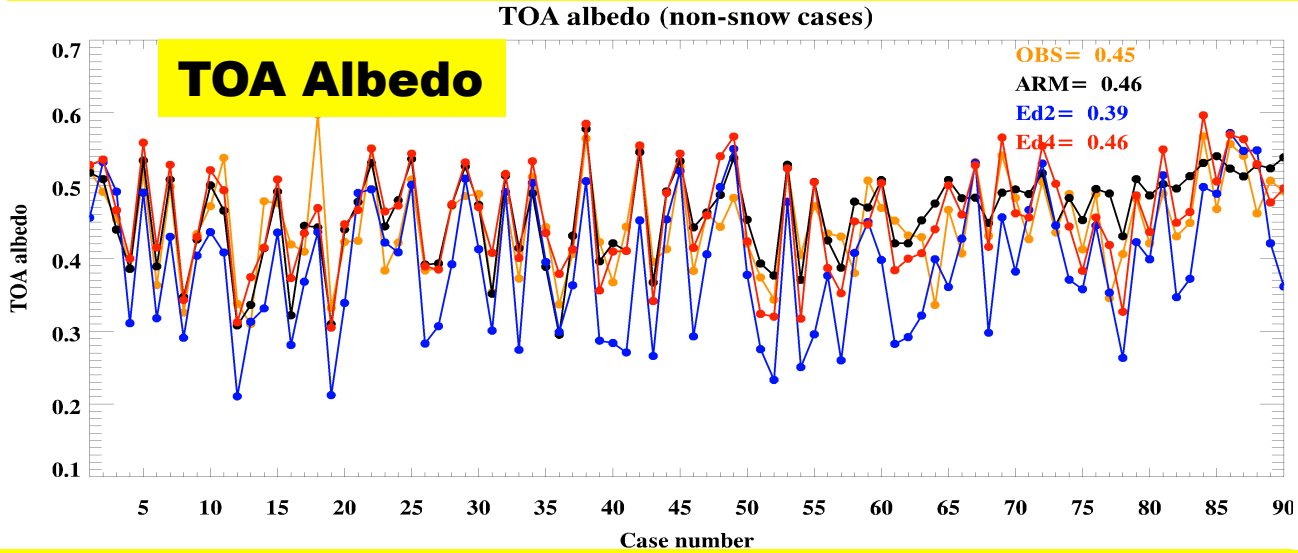
Surface Transmission

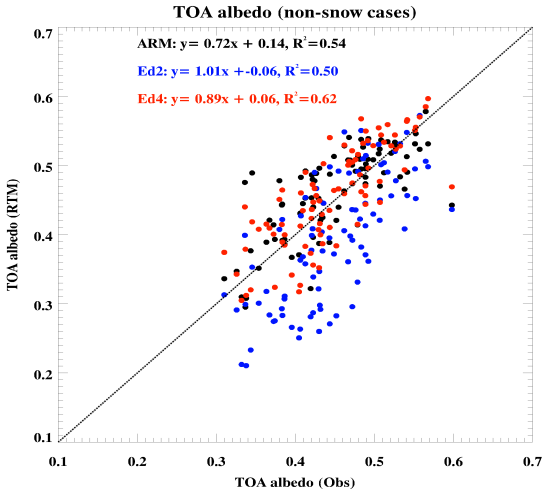




Ed4 and ARM are the same as ARM observed SW trans, but Ed2 is 0.13 higher.

TOA Albedo

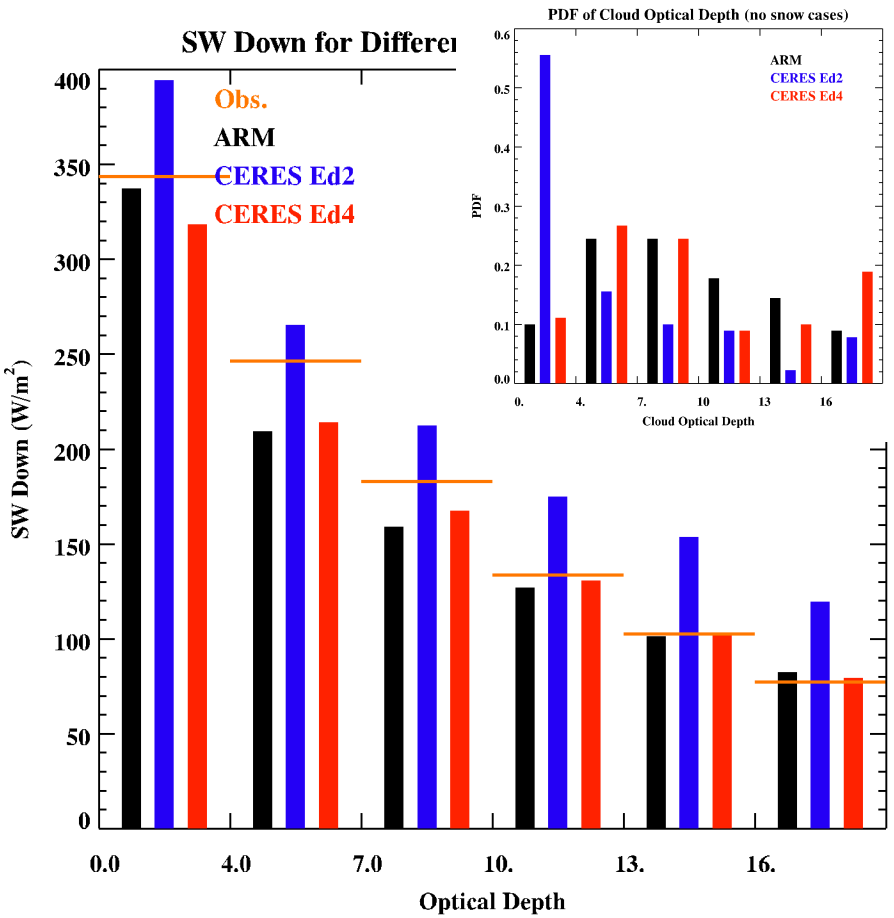


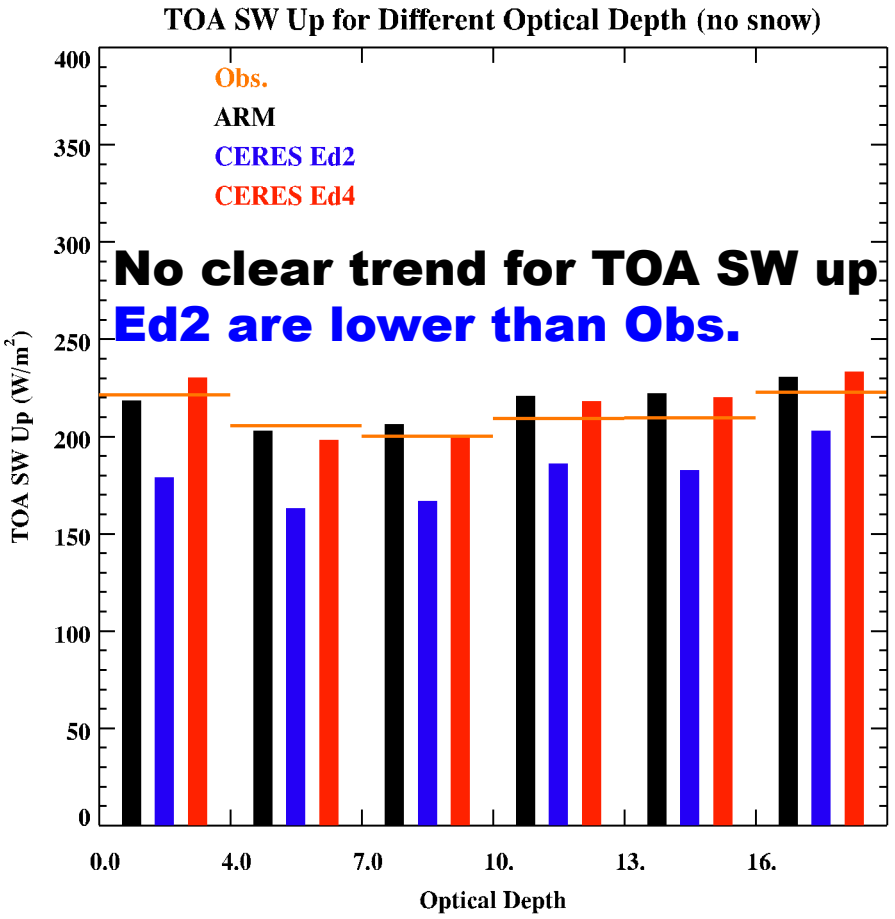


Again, Ed4 and ARM agree perfectly with CERES Obs, but Ed2 is 0.06 lower.

<u>Conclusion:</u> The excellent agreement in both surface transmission and TOA albedo indicate Ed4 and ARM retrieved cloud properties are correct, while Ed2 optical depth are too low.

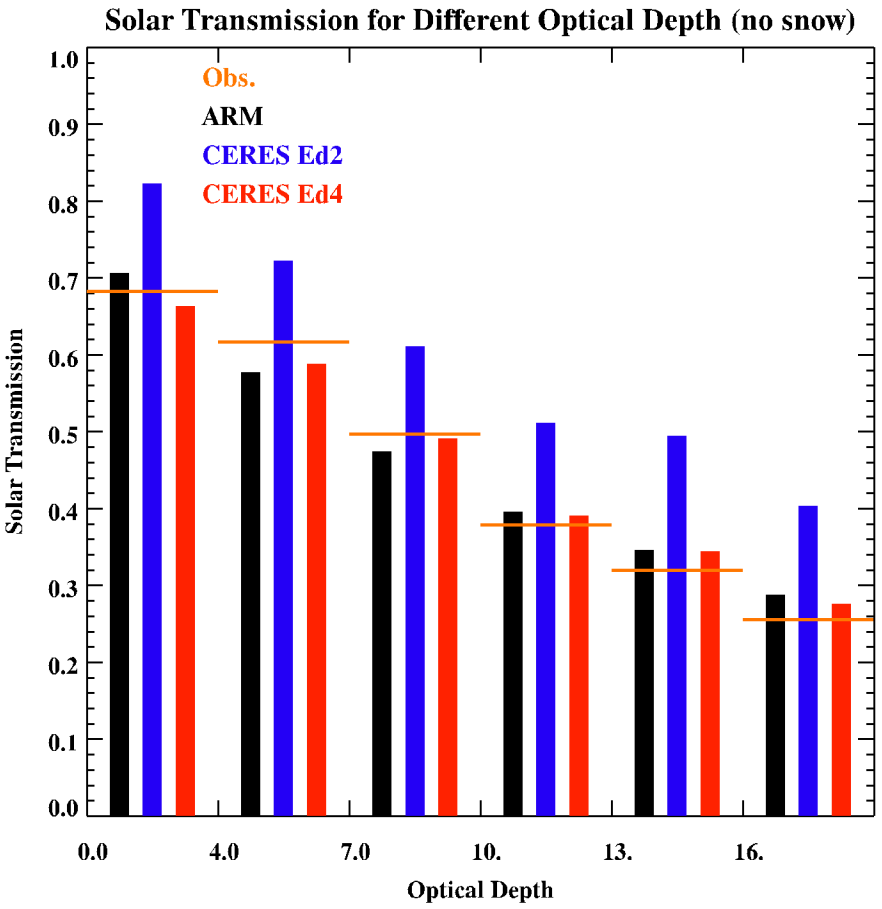
SW↓ and SW↑ Fluxes vs. Cloud Optical Depth

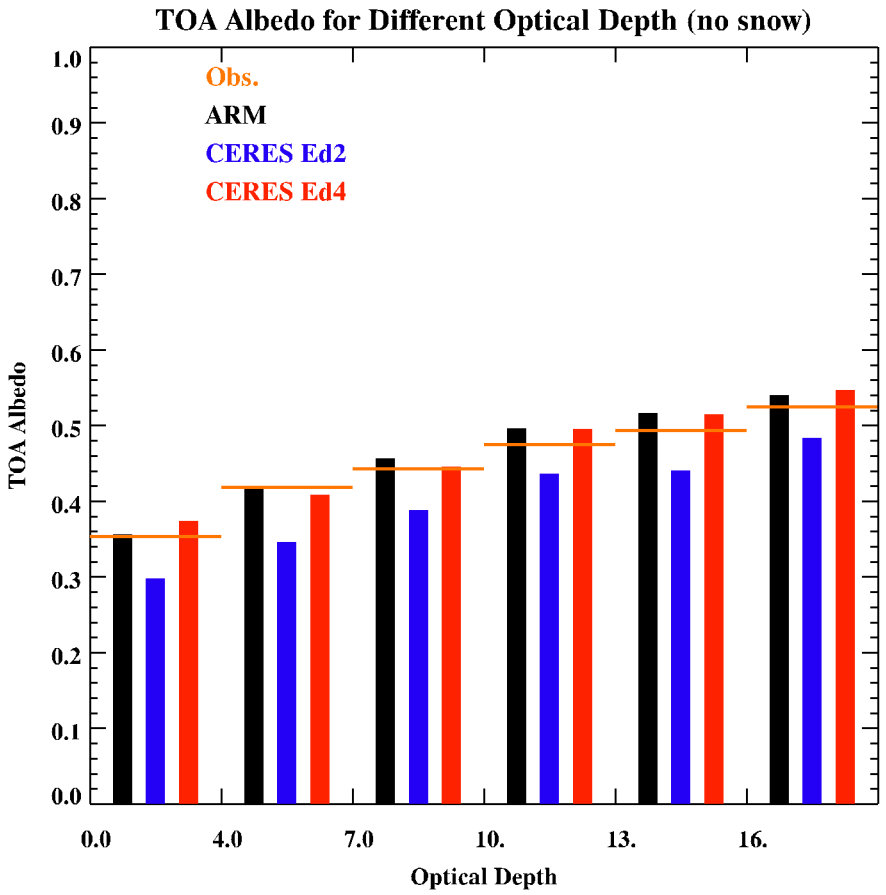




- **Surface SW↓ decreases with increased cloud optical depth.**
- **Ed4 and ARM SW↓ are lower than Surface Obs for tau < 10, close to Obs for tau> 10. Ed2 are higher than Obs for all tau values.**
- **Relative differences between Ed2 and Obs. increase with increasing tau, and overall >10% for all optical depth range**

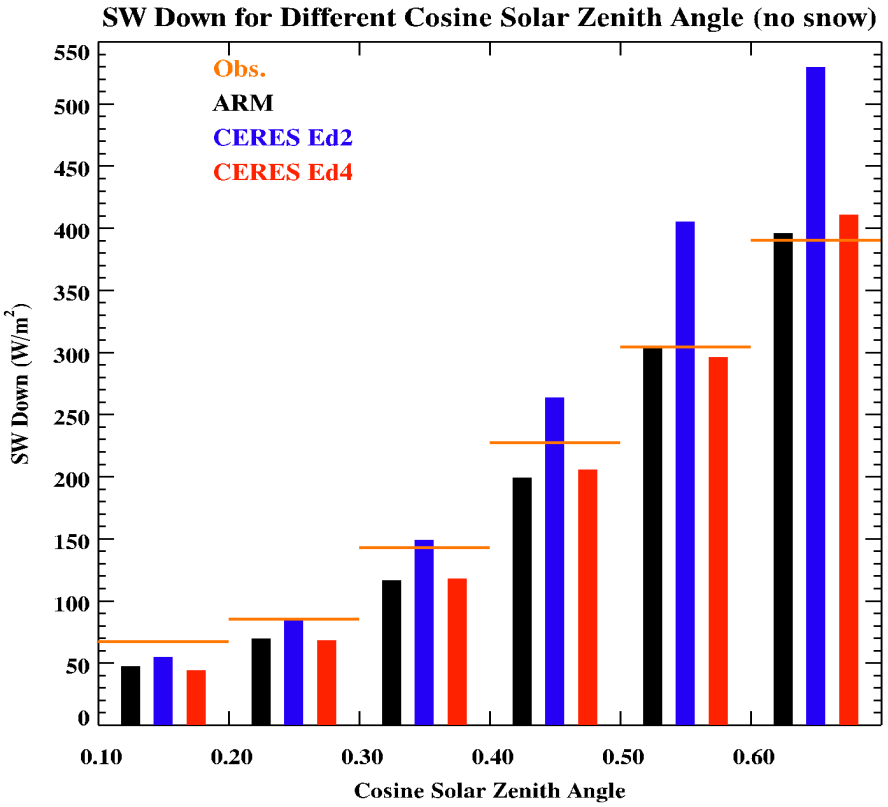
Surface Transmission and TOA Albedo vs. Cloud Optical Depth

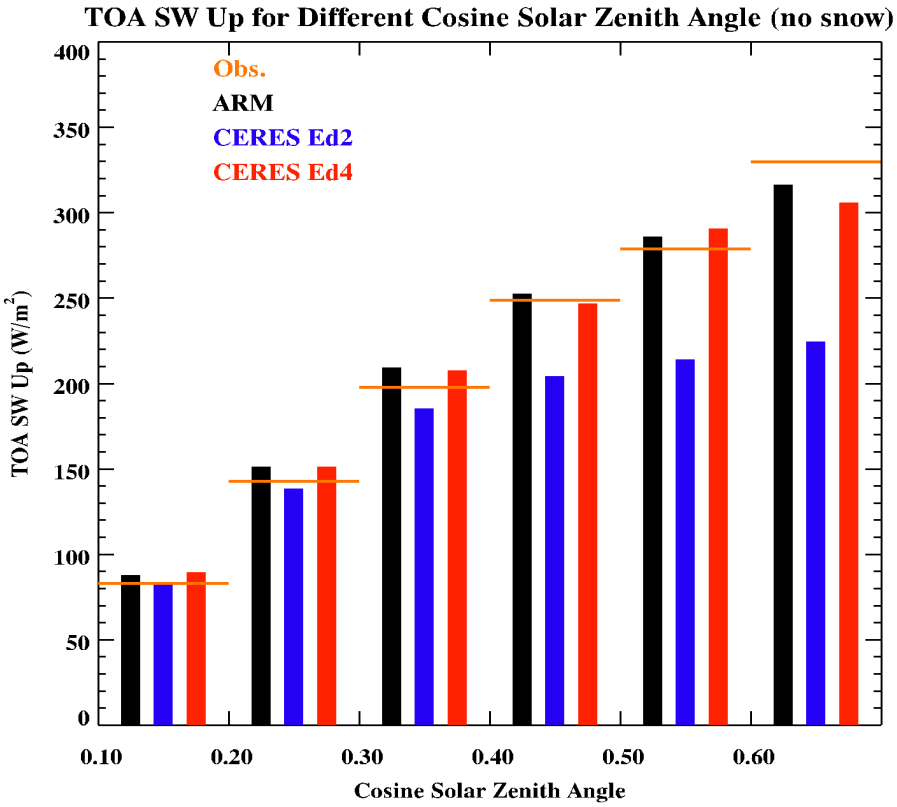




- **Surface SW transmissions decrease and TOA albedos increase with cloud optical depth.**
- **Both ARM and Ed4 agree well with Surface and TOA observations.**
- **Ed2 Surface transmissions > Obs and TOA albedo < Obs everywhere, indicating all Ed2 Tau values are underestimated.**

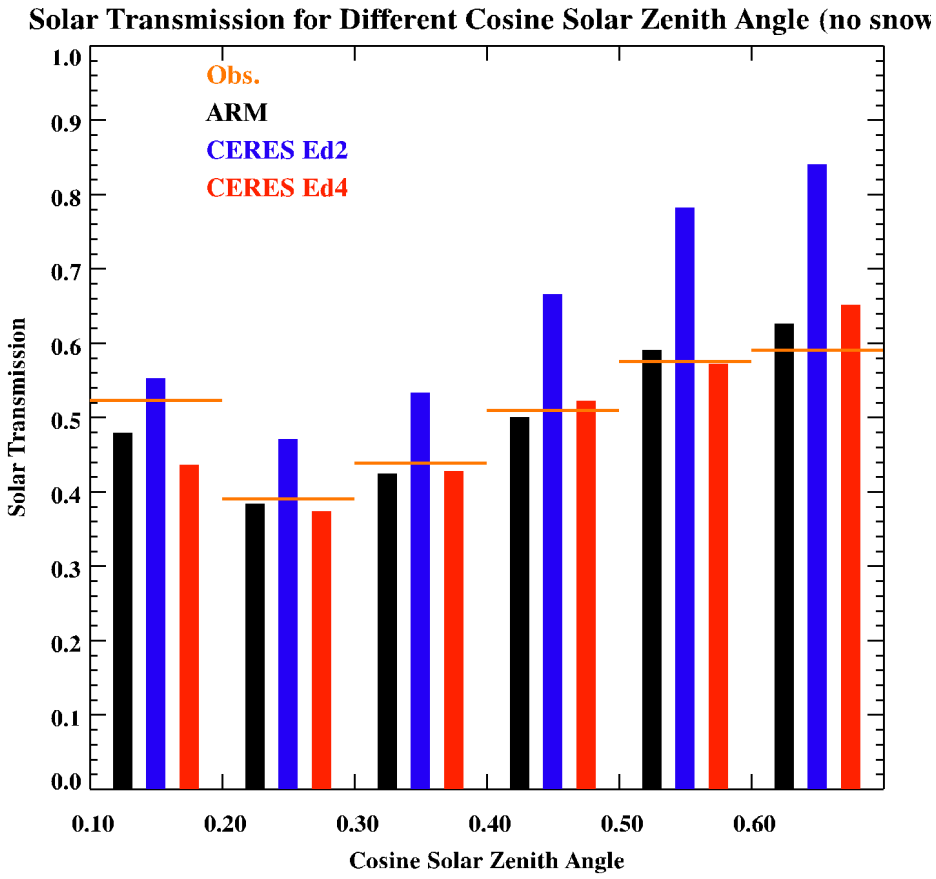
SW ↓ and SW ↑ fluxes vs. Cosine (SZA)

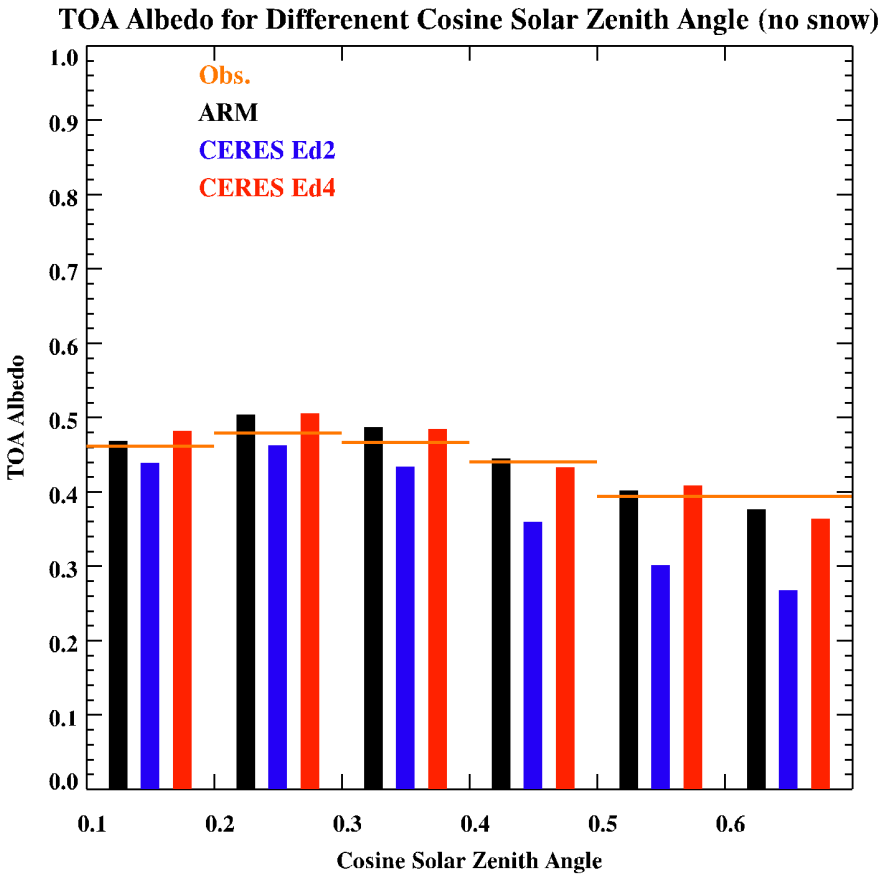




- **Both SW ↓ and SW ↑ fluxes increase with cosine (SZA), μ_0.**
- **Both calculated SW ↓ and SW ↑ fluxes with input of ARM and Ed4 cloud retrievals agree very well with Surface and TOA Obs for μ_0.**
- **Differences between Ed2 and Obs. increase with μ_0, and much larger for $\mu_0 > 0.4$.**

Surface Trans and TOA Albedo vs. μ_0





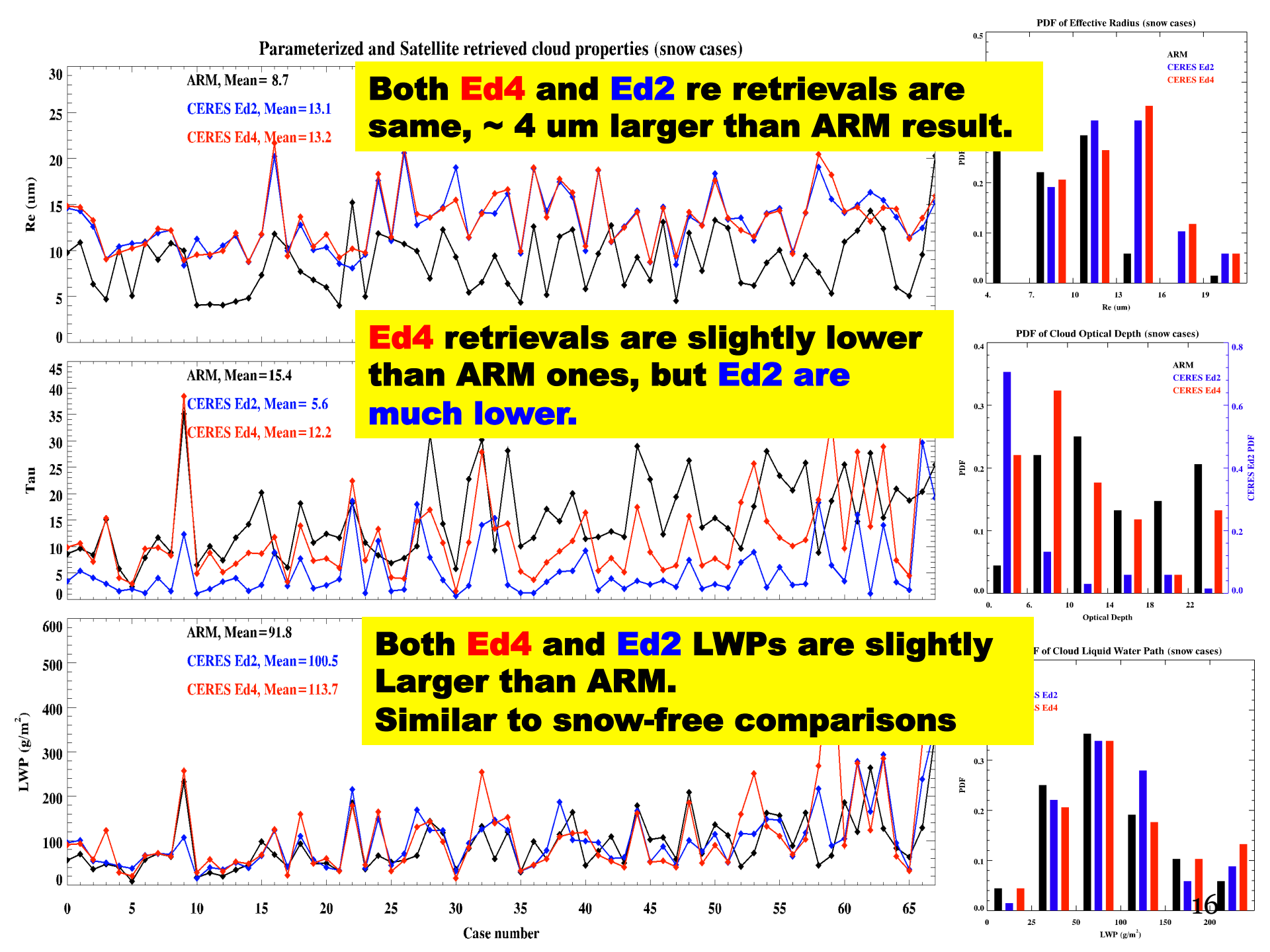
- **For surface transmission, it is similar to its flux comparison, increasing with μ_0, but TOA albedo decreases with μ_0.**

Summary I: snow-free cases (90)

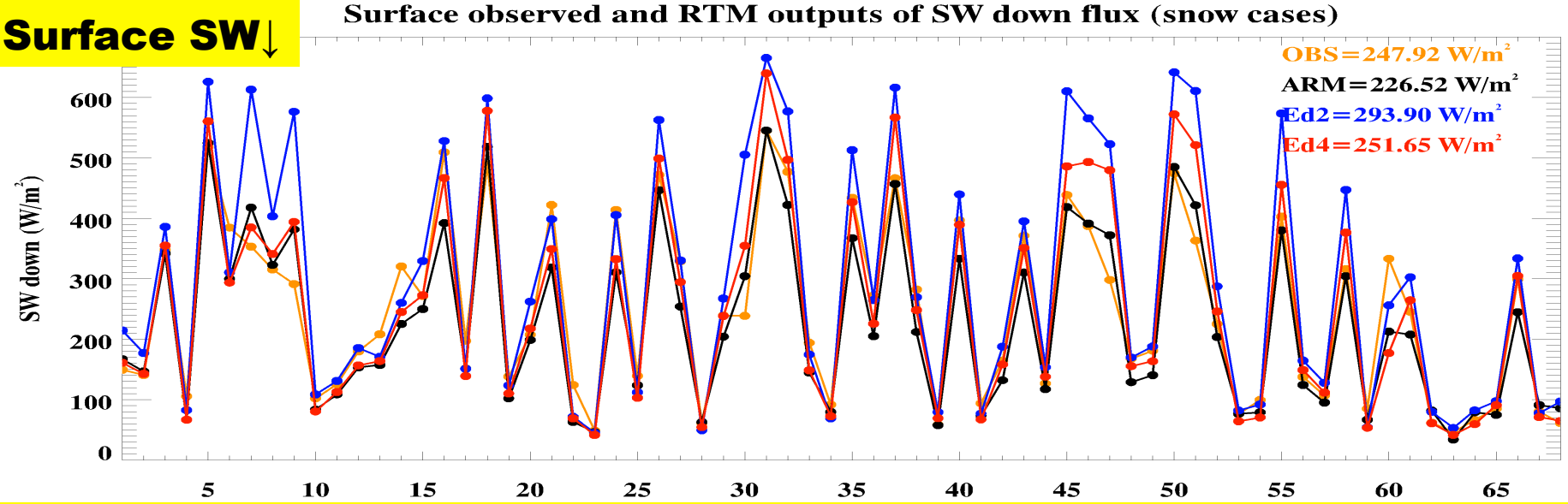
- **Ed4 and Ed2 re retrievals are ~ 2 um larger than ARM result, but Ed2 optical depth are ~half of ARM and Ed4.**
- **The excellent agreement in both surface transmission and TOA albedo indicate Ed4 and ARM retrieved cloud properties are correct, while Ed2 optical depth are too low.**
- **Surface SW transmissions decrease and TOA albedos increase with cloud optical depth. Both ARM and Ed4 agree well with Surface and TOA observations, while Ed2 Surface transmissions > Obs and TOA albedo < Obs everywhere, indicating all Ed2 Tau values are underestimated.**

Snow cases (68)

SURFACE ALBEDO > 0.3

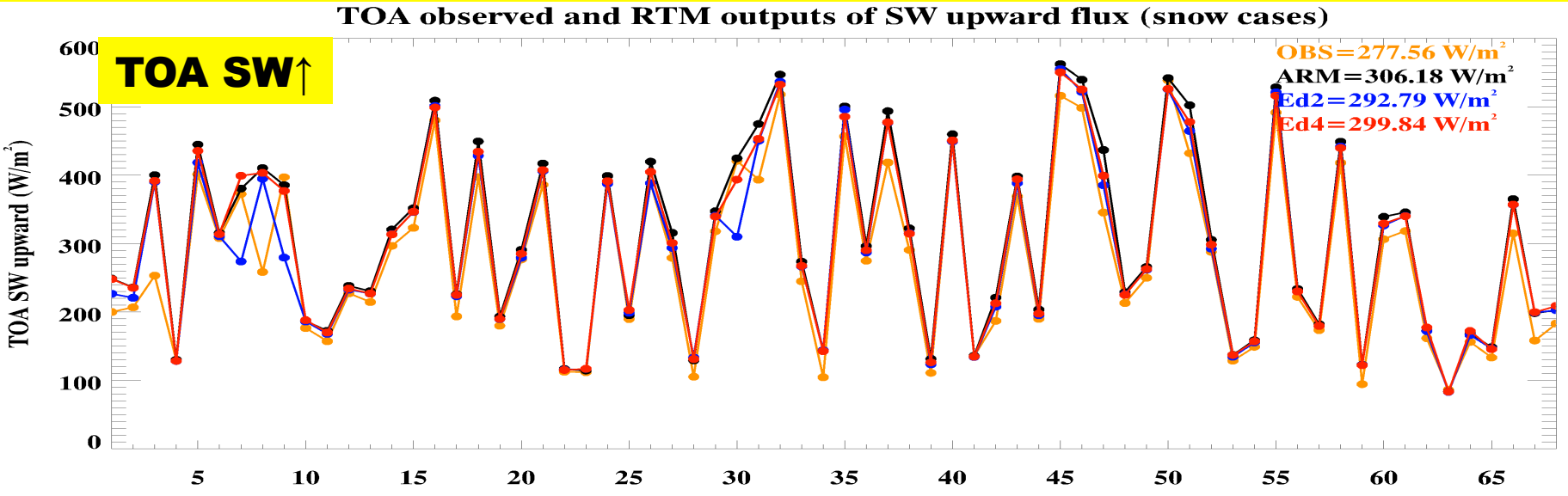

Parameterized and Satellite retrieved cloud properties (snow cases)
ARM, Mean= 8.7
CERES Ed2, Mean=13.1
CERES Ed4, Mean=13.2
Re (um)
Both Ed4 and Ed2 re retrievals are same, ~ 4 um larger than ARM result.
PDF of Effective Radius (snow cases)
ARM
CERES Ed2
CERES Ed4
Re (um)
ARM, Mean=15.4
CERES Ed2, Mean= 5.6
CERES Ed4, Mean=12.2
Tau
Ed4 retrievals are slightly lower than ARM ones, but Ed2 are much lower.
PDF of Cloud Optical Depth (snow cases)
ARM
CERES Ed2
CERES Ed4
PDF
CERES Ed2 PDF
Optical Depth
ARM, Mean=91.8
CERES Ed2, Mean=100.5
CERES Ed4, Mean=113.7
LWP (g/m2)
Both Ed4 and Ed2 LWPs are slightly Larger than ARM.
Similar to snow-free comparisons
F of Cloud Liquid Water Path (snow cases)
S Ed2
S Ed4
PDF
LWP (g/m2)
Case number

Surface SW↓



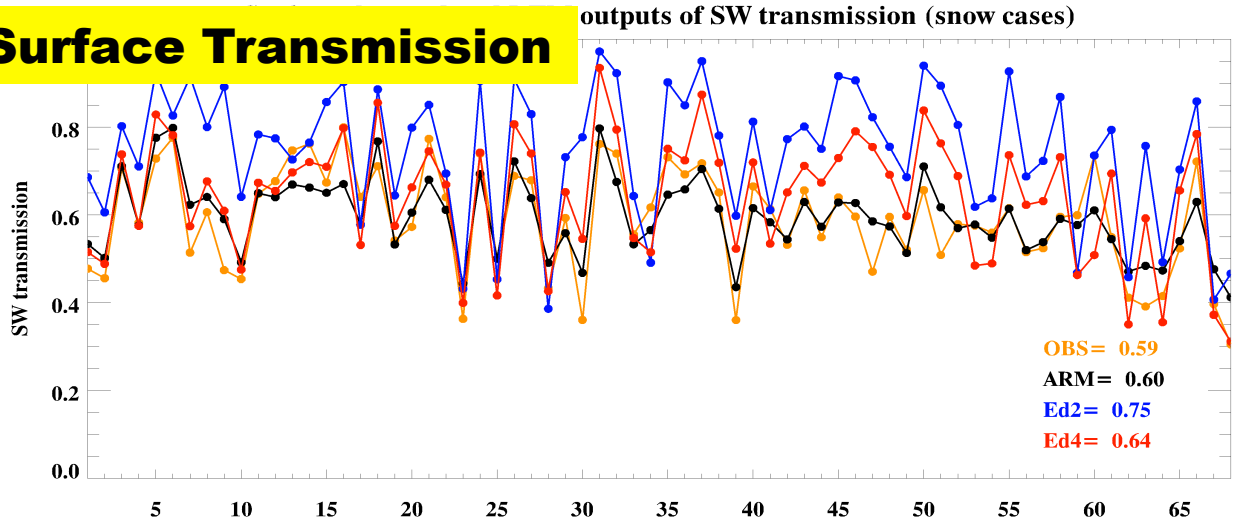
Compared to ARM Surface Obs, Ed4 and ARM are +3.8 Wm^{-2} and -21.4 Wm^{-2} , Ed2 is 46 Wm^{-2} larger, consistent to its lower optical depth (5.6 vs 12.2).

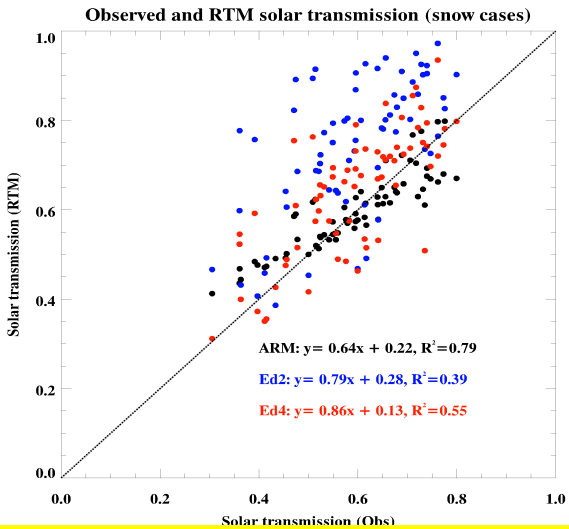
TOA SW↑



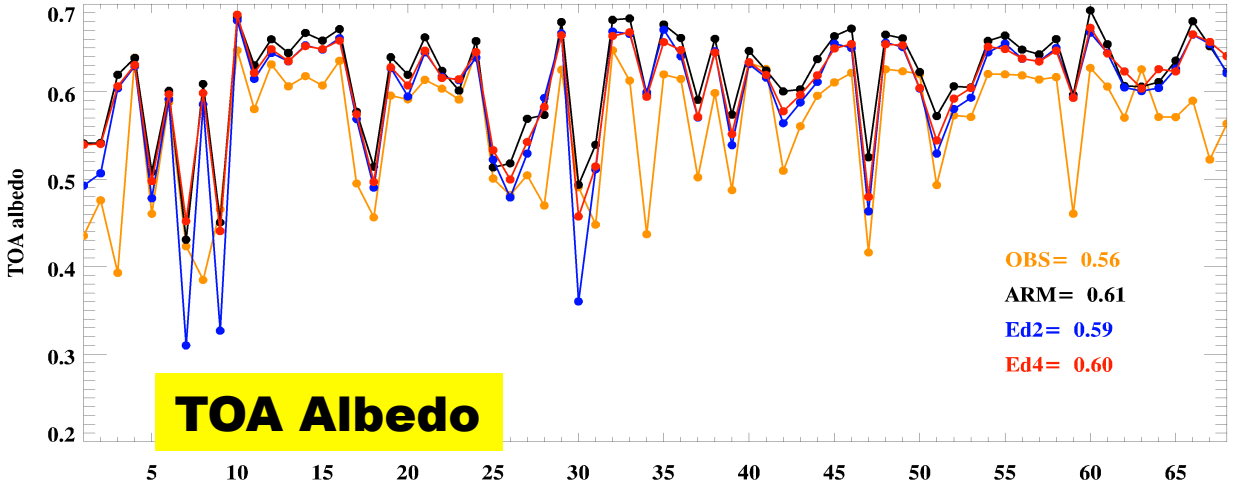
Compared to CERES result (277.6 Wm^{-2}), the differences for Ed2, Ed4 and ARM are +15.2, +22.2, and 24.6 Wm^{-2}, respectively.

Surface Transmission

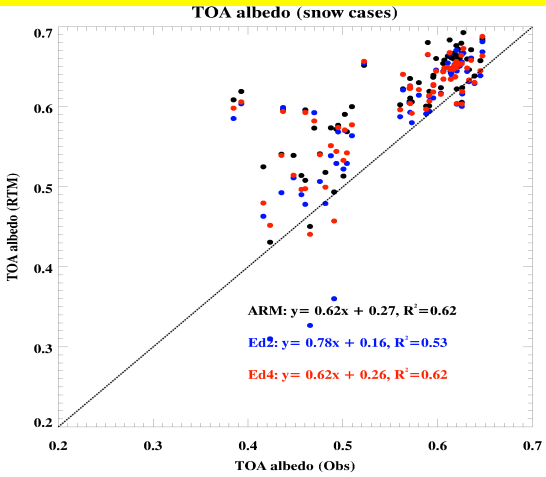




Compared to observed surface transmission (0.59), the differences for ARM, Ed4 and Ed2 are 0.01, 0.05, and 0.16 higher.



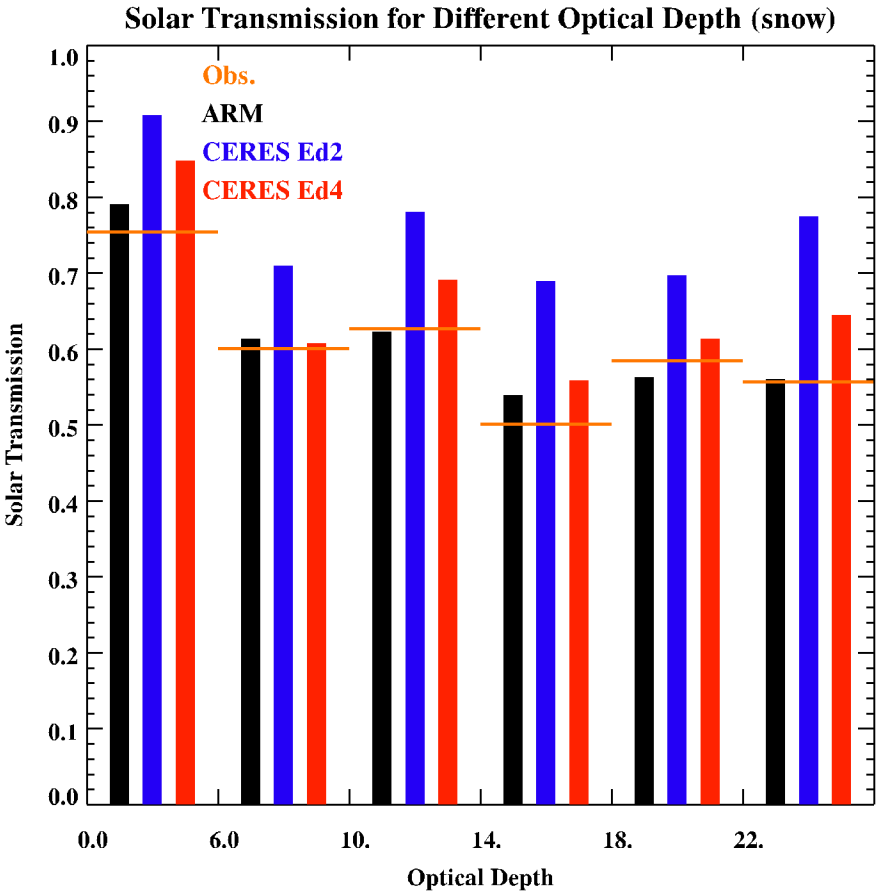
TOA Albedo

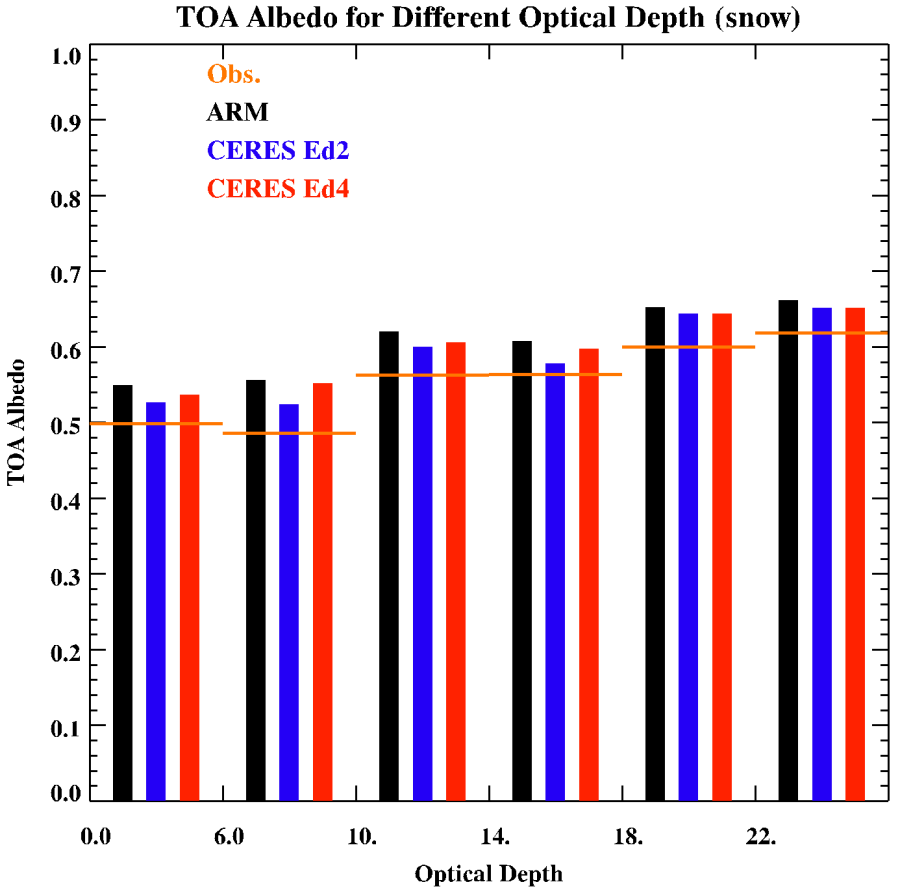


Compared to CERES observed TOA albedo (0.56), the differences for ARM, Ed4 and Ed2 are 0.05, 0.03, and 0.04 higher.

<u>Conclusion:</u> The good agreement in both surface transmission and TOA albedo indicate Ed4 and ARM retrieved cloud properties are correct, while Ed2 optical depth are too low (although its TOA albedo is close to Obs, due to snow surface)

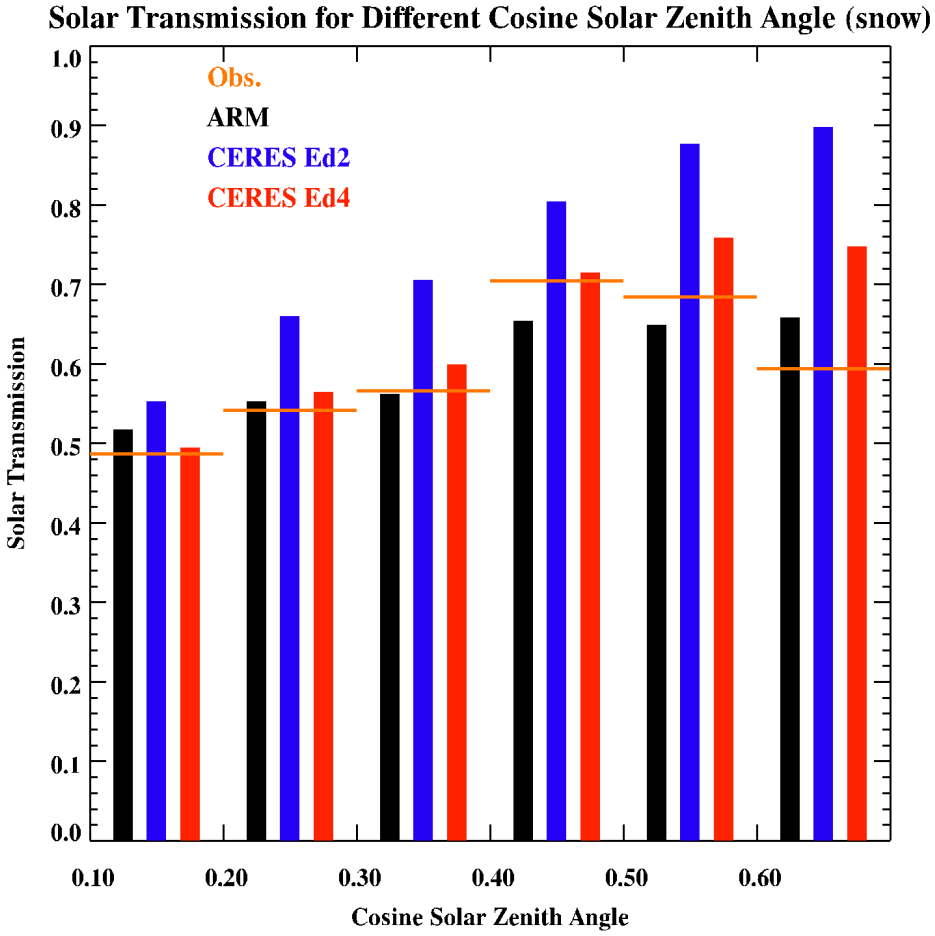
Surface Transmission and TOA Albedo vs. Cloud Optical Depth

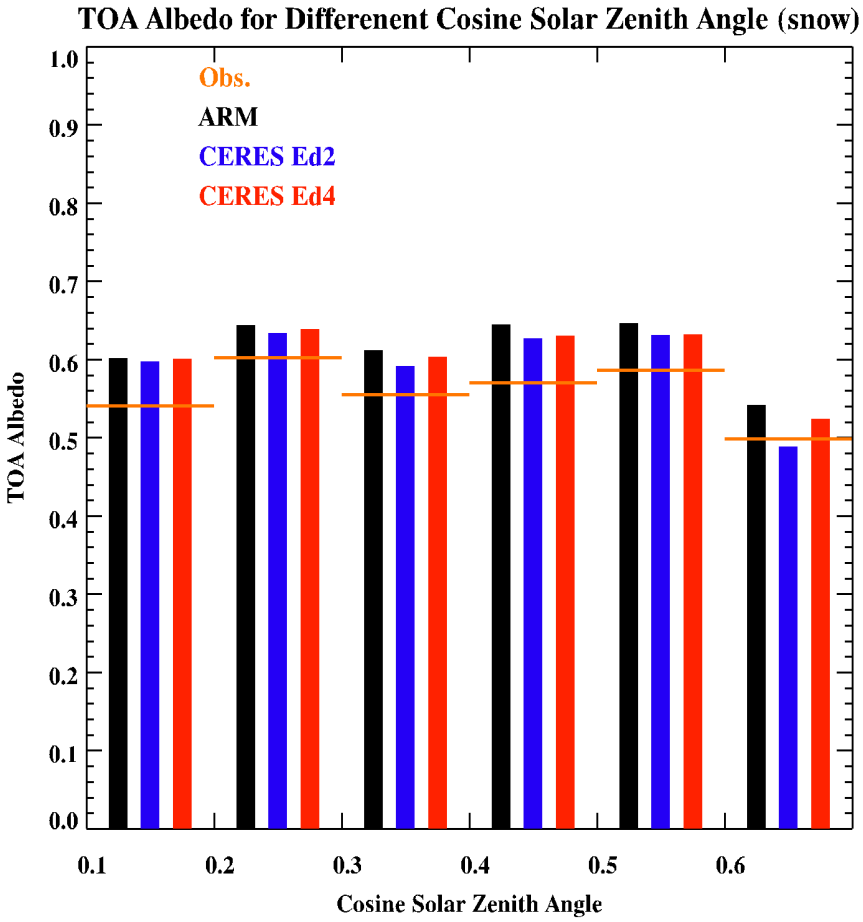




- **No clear trend for Surface transmissions, but TOA albedos increase slightly with cloud optical depth.**
- **ARM and Ed4 surface transmission agree well with Surface Obs, but Ed2 Surface transmissions > Obs for all tau values.**
- **All TOA albedos are slightly higher than CERES Obs.**
- **Compared to their snow-free values (0.48 and 0.45), both surface transmission and TOA albedo are 0.11 higher due to multiple reflections.**

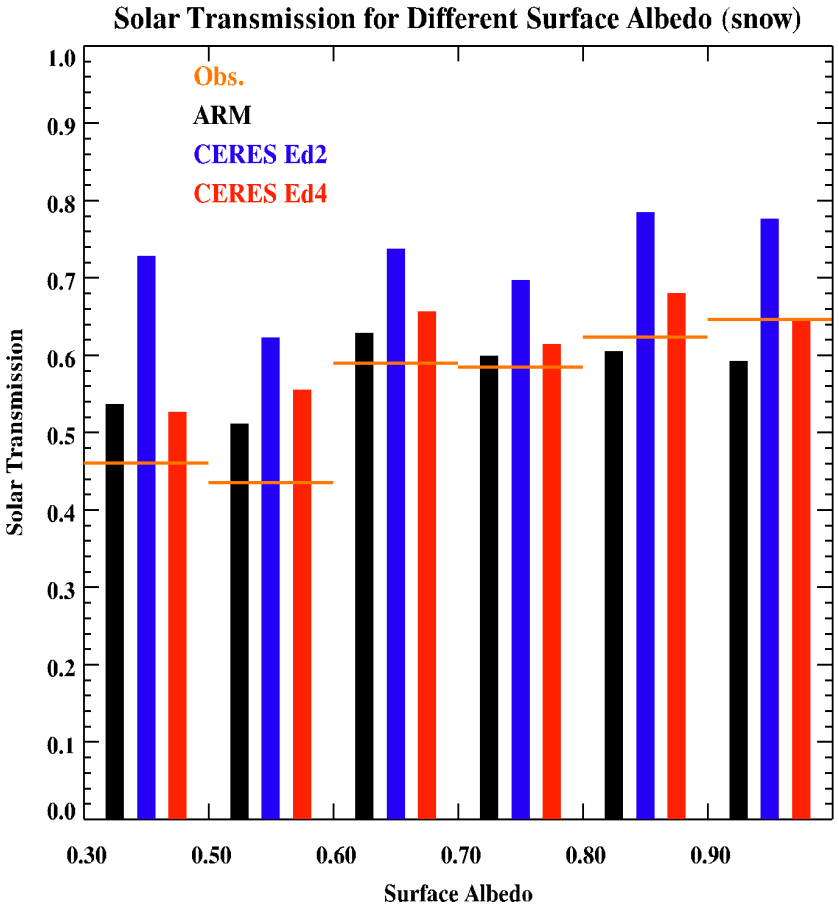
Surface Trans and TOA Albedo vs. μ_0

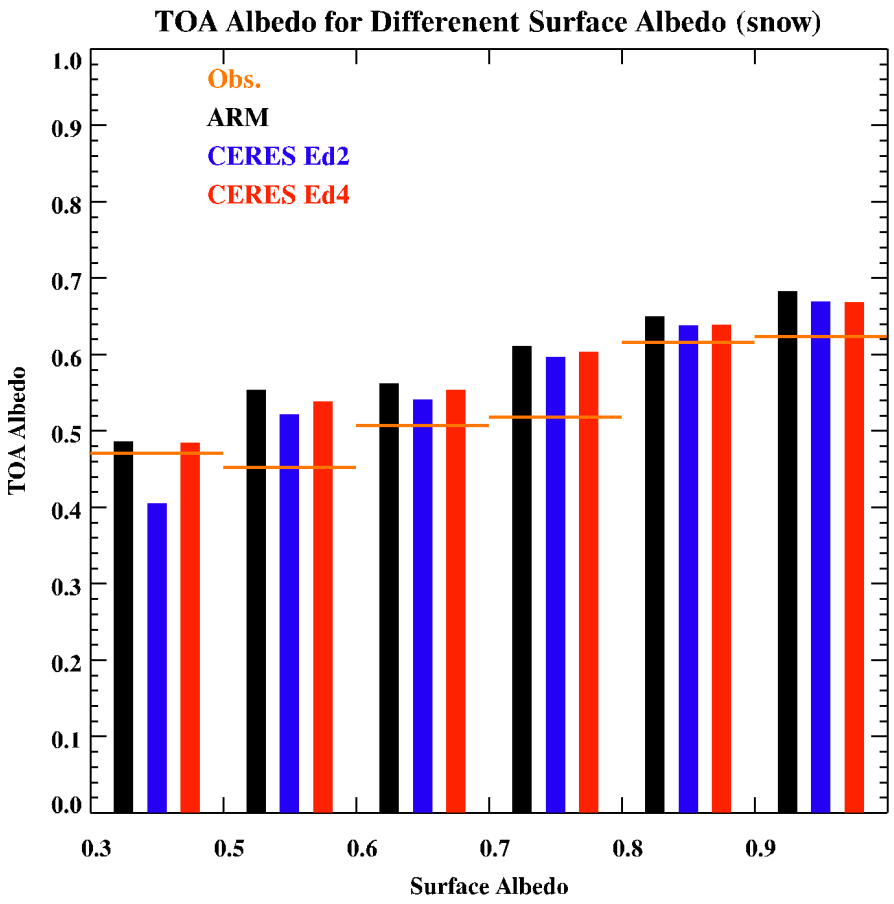




Similar to their snow-free comparisons, surface transmissions increase with μ_0, but TOA albedos keep constant or slightly decrease with μ_0.

Surface Trans and TOA Albedo vs surface albedo





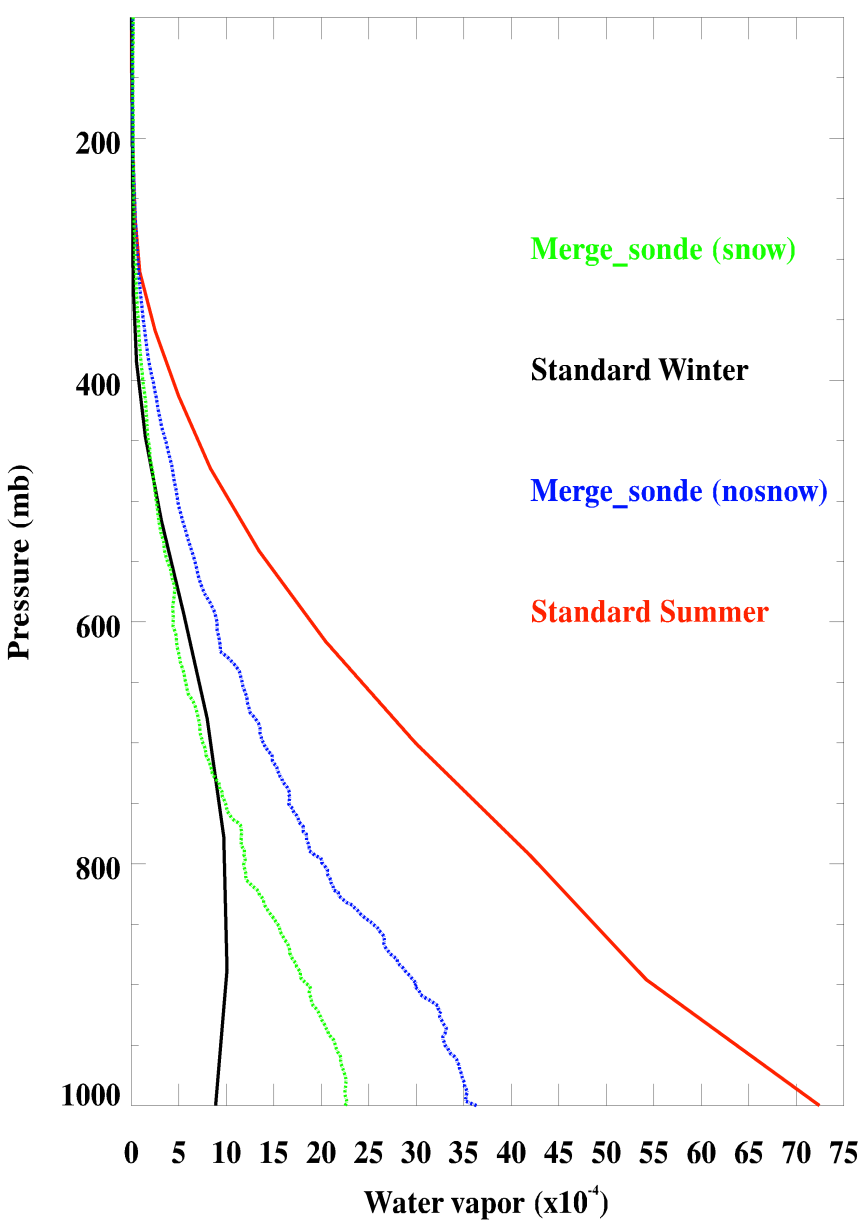
- **Surface transmissions and TOA albedos increase with increased surface albedo, due to multiple reflections between cloud layer and highly reflective snow surface.**

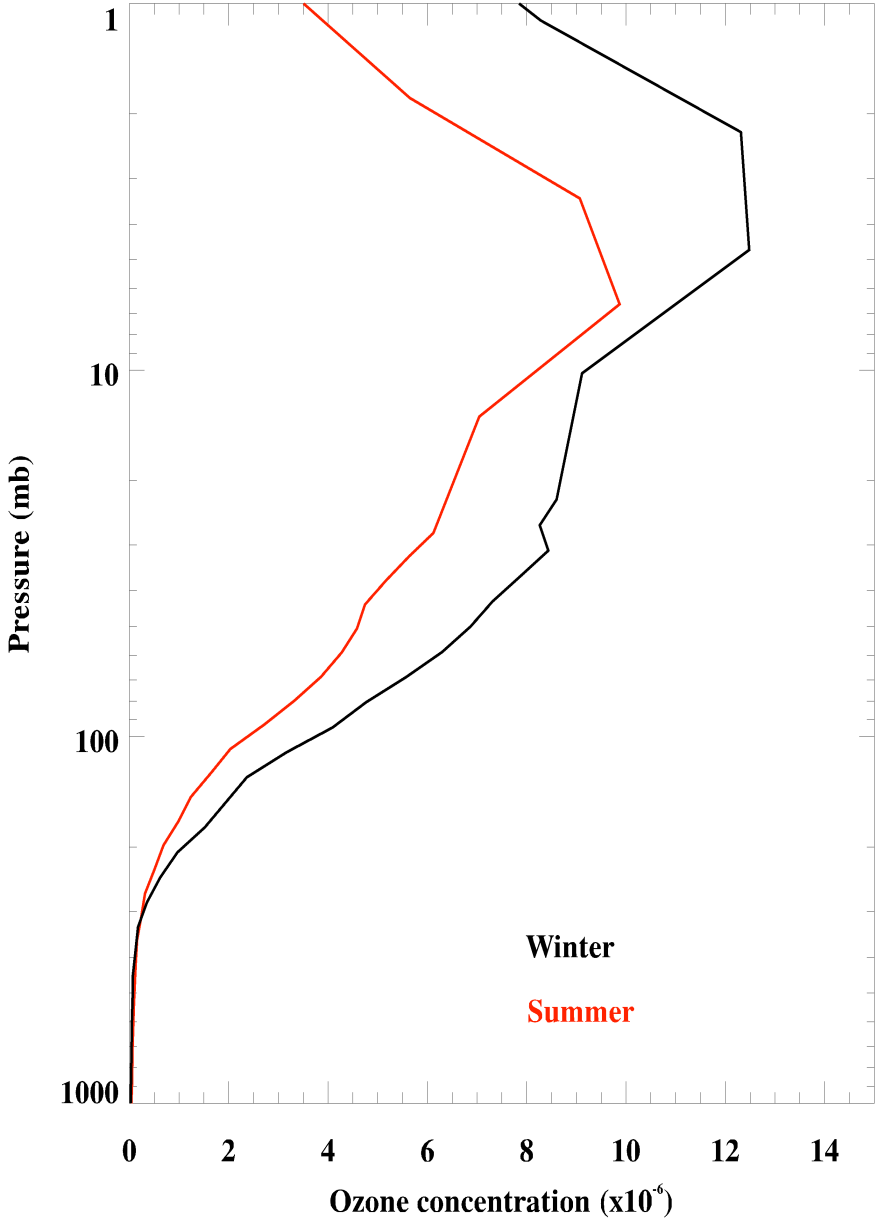
Summary II: snow cases (68)

- **Ed4 and Ed2 re retrievals are ~ 4 um larger than ARM result, but Ed2 optical depth are much lower than ARM and Ed4.**
- **The good agreement in both surface transmission and TOA albedo indicate Ed4 and ARM retrieved cloud properties are correct, while Ed2 optical depth are too low (although its TOA albedo is close to Obs, due to multiple reflections between snow surface and cloud layer)**
- **Compared to their snow-free values (0.48 and 0.45), both surface transmission and TOA albedo are 0.11 higher.**

Summary Table and Future Work

No_snow		TOA SW↓	TOA SW↑	R_{TOA}	SFC $SW\downarrow_{clear}$	SFC $SW\downarrow_{cloud}$	T_{trans}
Summer Profiles (T,P,q,O_3)	OBS	480.4	208.6	0.45	366.9	184.8	0.48
	ARM	481.8	213.6	0.46	329.4	168.2	0.47
	ED2		176	0.39		220.1	0.61
	ED4		211.5	0.46		170.2	0.47
Winter Profiles (T,P,q,O_3)	ARM	481.8	225.8	0.49	355.5	178.6	0.46
	ED2		185.9	0.42		234.6	0.60
	ED4		223.4	0.48		180.6	0.46
Snow							
Summer Profiles (T,P,q,O_3)	OBS	503.2	277.6	0.56	400.6	247.9	0.59
	ARM	504.8	306.2	0.61	363	226.5	0.60
	ED2		292.8	0.59		293.9	0.75
	ED4		299.8	0.60		251.7	0.64
Winter Profiles (T,P,q,O_3)	ARM	504.8	323.8	0.65	390.1	241.2	0.59
	ED2		311.3	0.63		313	0.74
	ED4		317.3	0.64		267.6	0.63


Merge_sonde (snow)
Standard Winter
Merge_sonde (nosnow)
Standard Summer
Pressure (mb)
200
400
600
800
1000
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
Water vapor (x10-4)


Winter
Summer
Pressure (mb)
1
10
100
1000
0 2 4 6 8 10 12 14
Ozone concentration (x10-6)

Summary Table and Future Work

No_snow		TOA SW↓	TOA SW↑	R_{TOA}	SFC $SW\downarrow_{clear}$	SFC $SW\downarrow_{cloud}$	T_{trans}
Real Atmos. Profiles (T,P,q,O_3)	OBS	480.4	208.6	0.45	366.9	184.8	0.48
	ARM	481.8	214/220	0.46/0.47	329.4/ 339.2	168/173	0.47/0.47
	ED2		176/181	0.39/0.41		220/227	0.61/0.60
	ED4		212/218	0.46/0.47		170/175	0.47/0.47
Snow							
Real Atmos. profiles	OBS	503.2	277.6	0.56	400.6	247.9	0.59
	ARM	504.8	306/321	0.61/0.64	363/ 383	227/237	0.60/0.59
	ED2		293/307	0.59/0.62		294/308	0.75/0.74
	ED4		300/314	0.60/0.63		252/263	0.64/0.63

Using the real soundings, the surface clear-sky and cloudy SW down agree better with ARM observations, but the TOA SW up differences become larger, particular for snow cases.

Measured at Top of Atmosphere
Solar constant=$\int E_\lambda d\lambda$=1365 Wm^{-2}

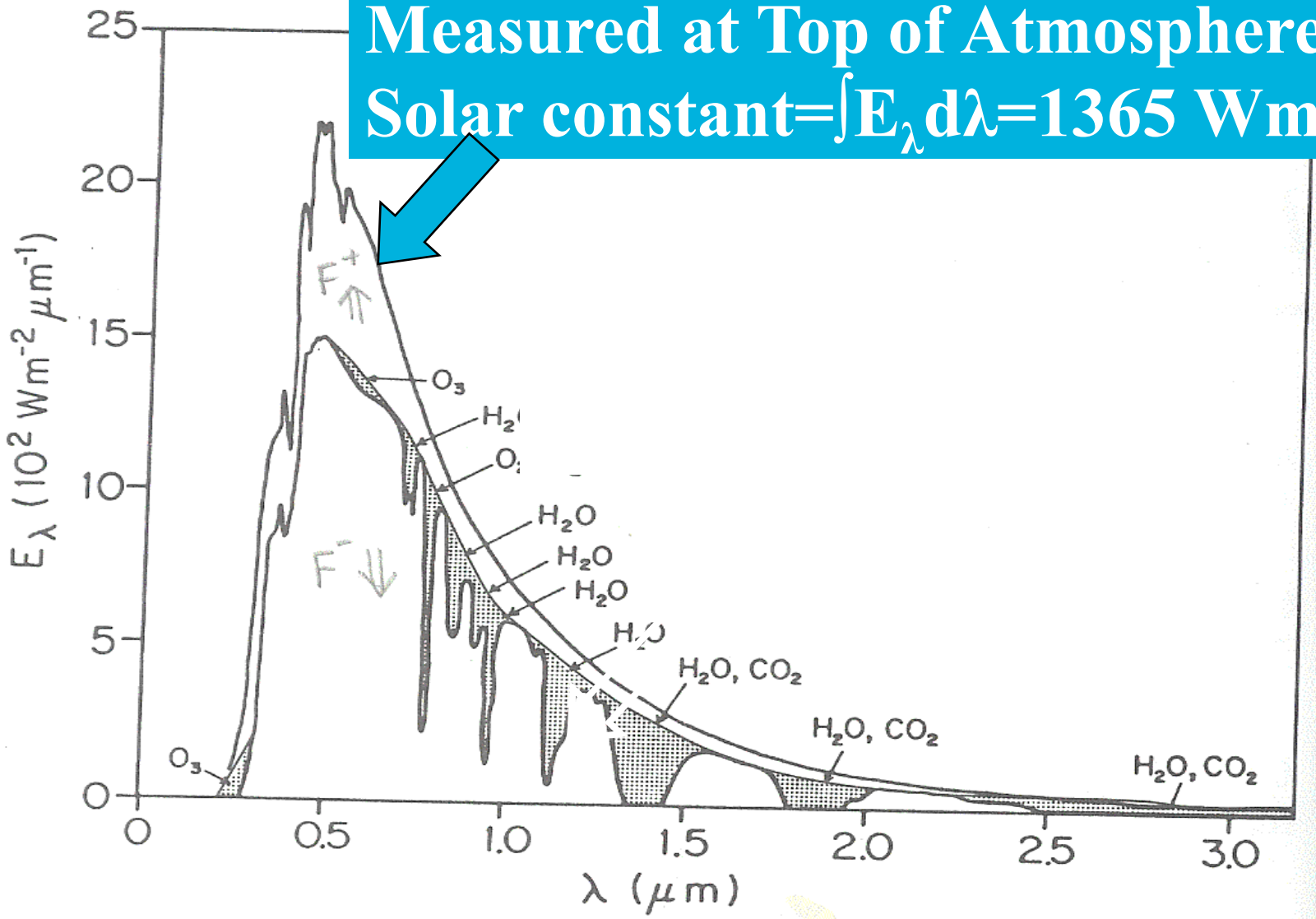
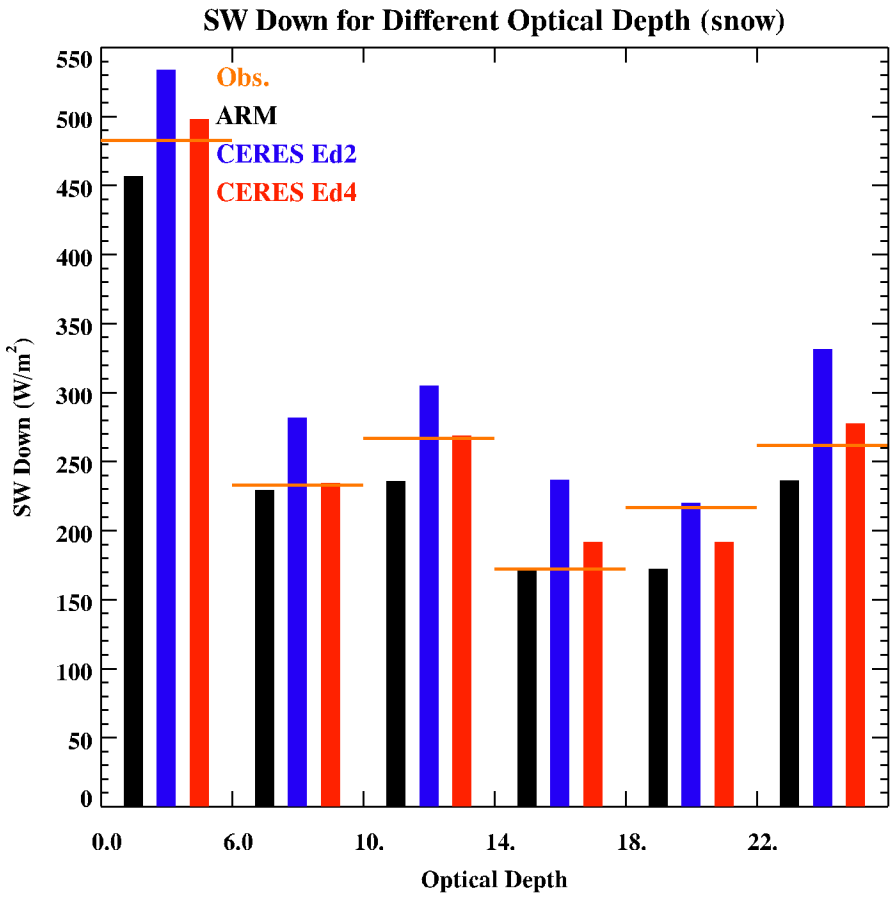
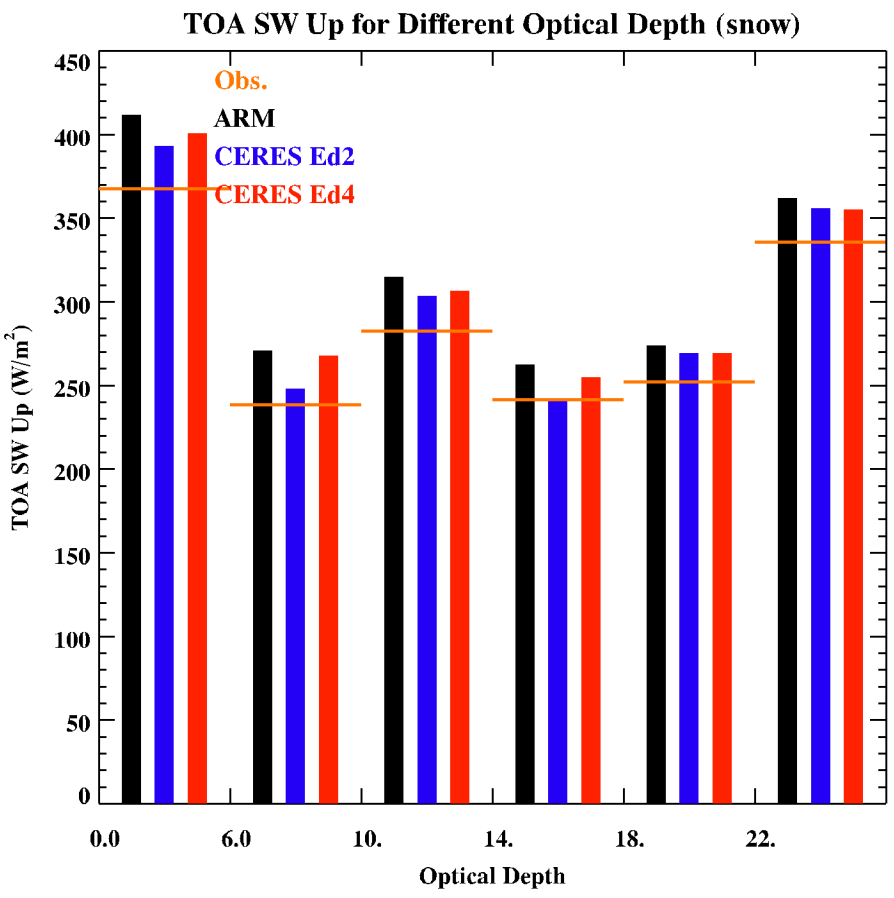


FIGURE 6.1. Spectral distribution of solar irradiation at the top of the atmosphere and at sea level for average atmospheric conditions for the sun at zenith. The shaded areas represent absorption by various atmospheric gases. The unshaded area between the two curves represents the portion of the solar energy backscattered by the air, water vapor, dust, and aerosols and reflected by clouds. For the curve at the top of the atmosphere the integral $\int_0^\infty E_\lambda \, d\lambda \simeq 1360 \text{ W m}^{-2}$ represents the solar constant (adapted from Gast, 1965).

SW ↓ and SW ↑ Fluxes vs. Cloud Optical Depth





- **No clear trend for both SW down at surface and TOA SW Up with increased tau.**
- **Both SW down at surface and TOA SW up fluxes are higher than snow-free results due to multiple scattering between cloud layer and snow surface.**
- **Ed4 and ARM SW down agree with Surface Obs, but Ed2 are higher than Obs for all tau values.**
- **All TOA SW up fluxes are slightly higher than CERES Obs.**